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FINAL TECHNICAL REPORT

for

CONTROL SYSTEMS AND NETWORKS

under

AFOSR-78-3546

Air Force Office of Scientific Research (AFSC)
Bolling Air Force Base, DC 20332

Principal Investigator: Professor James S. Meditch

March 1982

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UNIVERSITY OF WASHINGTON
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ABSTRACT

Research conducted under AFOSR Grant 78-3546, Control Systems and Networks, during the four-year term of the grant, 1 February 1978 to 31 January 1982, is summarized and highlighted. The work is classified into the two major categories of (1) control systems and (2) networks. Within the former, new results are reported in the areas of vector-delay inverses, pseudoinverses, fixed-lag smoothing realizations, and the design of multivariable control systems using system inverses. In the second category, the focus is on the problems of modeling, analysis, optimization, and control of large-scale, distributed networks for C^3 . Specific topics dealt with include hierarchical control, decomposition, and distributed intelligence in network performance optimization, the theory of aggregated imbedded Markov chain models and distributed control of large-scale computer-communication networks, the packet formation process in packet-switched networks, centralized and decentralized optimal flow assignment and routing in networks via the minimum hop technique subject to message delay constraints, and minimum cost channel capacity design of networks. Listings of the publications and Ph.D. theses resulting from this grant are given.

I. INTRODUCTION

This document is the final technical report for AFOSR Grant 78-3546, Control Systems and Networks. The term of the grant was the four-year period 1 February 1978 to 31 January 1982, inclusive. The Principal Investigator was Professor James S. Meditch, Department of Electrical Engineering, University of Washington, Seattle.

The research conducted under this grant falls into the two categories of (1) Control Systems and (2) Networks. Within the former category, work was carried out in the areas of vector-delay inverses, pseudoinverses, fixed-lag smoothing, and the design of multivariable control systems using the theories of system inverses. The results of this work are summarized in Section II.

In the category of Networks, research was pursued on the problems of modeling, analysis, optimization, and control of large-scale distributed networks for C^3 . Specific issues addressed were those of hierarchical control, decomposition, and distributed intelligence in the optimization of network performance, the theory of imbedded Markov chains and the techniques of aggregation for distributed optimal control of C^3 networks, modeling and performance analysis of the packet-formation process in packet-switched networks, formulation of a very fast algorithm for approximate solution of the optimal routing problem for message and packet-switched networks, optimal channel capacity assignment in networks subject to end-to-end average message delay constraints, and centralized and distributed algorithms for minimum hop routing subject to average message delay constraints. The results of this research are presented in Section III.

A chronological bibliography of journal and conference paper publications resulting from this grant is given in Section IV.

In addition to the work of the Principal Investigator, the grant supported in part the doctoral research of 3 graduate students. A chronological listing of the Ph.D. research so conducted is presented in Section V.

The project personnel during the term of the grant are listed in Section VI.

II. CONTROL SYSTEMS

A theory of inverses for discrete-time stochastic linear systems was developed in [1] utilizing the methods of fixed-lag smoothing. The structure of this class of inverses was shown to be that of a multi-variable finite-impulse-response (FIR) digital filter whose input is the innovations process from the Kalman filter for the original system. It was demonstrated theoretically that these inverses always exist and are stable under the same conditions that guarantee existence and stability, respectively, of the Kalman filter for the original system. Synthesis of these inverses is extremely simple utilizing existing microprocessor technology.

The research in [2,3,5] has solved the problem of stable realization of fixed-lag smoothers for continuous-time random processes. The realizations are in the form of partial differential equations and are the simplest ones possible which are also theoretically exact. When specialized to stationary processes, they lead to a time-domain input/output model which is amenable to approximate realization via the methods

of digital signal processing. On the other hand, the exact presentations indicate the type of device technology that must be developed to cope with the problem of continuous-time, fixed-lag, smoothing. Since fixed-lag smoothers generally provide smaller estimation error variances than do corresponding Kalman filters, the development of devices to implement the former is worthy of pursuit. A significant feature of the new representations is that they are both input/output and internally stable, whereas earlier realizations, while input/output stable, were internally unstable.

The research presented in [4,7] has provided a unified treatment of the linear multivariable system inverse problem with applications in feedback control. Both time and frequency domain, and deterministic and stochastic, system descriptions are included.

The concept of vector-delay inverses was formulated and shown to encompass all previous work on system inverses as special cases. Two algorithms for determining vector-delay inverses were developed; these algorithms automatically determine the classical minimal-delay inverse when the vector-delay inverse does not exist.

Another new notion that was pursued in this research was that of partial inverses. When neither the vector-delay inverse nor the classical inverse of a system exists, the question arises as to whether or not some of the unknown inputs to a system can still be recovered. Our research led to an algorithm which answers this question in detail. The algorithm proceeds as follows: (1) it determines whether or not the classical and vector-delay inverses exist; if they do, it determines them both; if only the classical one exists, it provides that inverse;

if neither one exists, it proceeds to the second step; (2) the algorithm determines which inputs are recoverable and provides both the transfer matrix and state-space descriptions of the dynamic system which recovers these inputs with minimal vector delay.

Using the above results, a new inverse system/state observer structure was developed which can be used in feedback control of systems which have extraneous signals that are of unknown origin, i.e., cannot be modeled either deterministically or stochastically. The new structure simultaneously provides an estimate of both the unknown signals and the system state. The theory shows that this information has an inherent delay which cannot be reduced. This means that feedback control will be subject to such delay. However, there do exist feedback control synthesis methods for systems with delayed information.

III. NETWORKS

The research in [10] provides a general framework for the dynamic modeling of large-scale distributed networks. The theory of imbedded Markov chains and the techniques of aggregation were used to develop distributed optimal control procedures for networks in which (1) there is contention for limited computing and communication resources by many users, (2) control must be distributed due to geographical and reliability considerations, and (3) network state information is generally distributed, delayed, and incomplete. Applications of interest include terrestrial, satellite, and ground/sea radio networks. The use of aggregation techniques significantly reduces the dimensionality of the distributed optimal control problem which must be solved, both in terms of the control information which must be exchanged between network nodes and the computations

which must take place at the nodes. This research also dealt with the computational details of implementation subject to minimization of control information exchange between nodes.

In [11,15], queueing models for the performance analysis of the packet formation process, i.e., the conversion of messages into packets, in packet-switched networks were developed and illustrated. The models are specified by the four parameters of average message arrival rate, average message length, maximum length of the text field in a packet, and processor time to form one packet. The results provide the performance characteristics and tradeoffs of the packet formation process, and can be used to specify processor speed as a function of the other system parameters in order to meet packet formation delay constraints. Extensions of this research addressed the issues of modeling for messages with priorities, parallel processing, and the effects of errors in packet formation.

Research on message routing and flow assignment was conducted along three separate, but related, directions. In all cases, the underlying problem was that of specifying paths for multicommodity message flow between all source-destination pairs in a message or packet-switched network to achieve desired delay-throughput characteristics. In [6,9], the goal and model coordination techniques of optimization theory were used to develop a distributed algorithm for message routing to minimize average message delay over all source-destination pairs. The algorithm is in two parts of which the first solves the optimal total flow assignment problem and the second provides the corresponding commodity-by-commodity routing

at each node. All calculations are distributed among the nodes, and require information only from adjacent nodes. The principal advantage of this two-part algorithm over previously proposed algorithms resides in the nature of the calculations required at the nodes. Specifically, this new algorithm requires the solution of linear programs at each node whereas earlier algorithms required convex programs. Simulation results demonstrated rapid convergence and indicated possible simplifications for practical implementation.

The second line of research on routing and flow assignment [8] drew upon the one above to develop an approximate solution of the problem. The approximation was via a surrogate performance function which bounds the average message delay from above. The resulting distributed routing algorithm has the following properties: (1) it is in two parts, similar to that above, in which the first part solves the total flow assignment problem and the second gives the commodity-by-commodity routing, (2) the first part always converges in two iterations, while the second part requires no iterations, (3) the routing is conservative with the actual average message delay being less than or equal to the calculated one, (4) the error in the approximation is easily calculated exactly, and (5) the algorithm is faster than all other existing ones. It should also be noted in connection with this algorithm that the information exchange required between nodes is only between adjacent nodes.

The third direction of the research addressed the routing and flow assignment problem in a novel and practically very attractive fashion. The usual, and essentially classical, formulation of the problem speci-

fies minimization of average message delay. In [13], the notion of minimum hop flow assignment and routing subject to a set of one or more end-to-end (source-to-destination) delay constraints was introduced and exploited to initiate the development of a new theory. The effect of minimizing the number of hops that messages make in proceeding from source to destination was shown to minimize network overhead, control traffic, and the effects of message errors due to channel noise and nodal processing. The use of end-to-end message delay constraints then serves further to meet user requirements for the timely delivery of messages, particularly for critical source-destination node pairs.

The main result in [13] was a centralized algorithm for minimum hop routing which uses search techniques. An initial feasible flow which provides minimum hop routing independent of the end-to-end constraints is first established, and then flow deviation is used iteratively to satisfy the constraints. Numerical studies conducted for an 8 node, 14 link network with 7 commodities exhibited excellent convergence results. Additional work on minimum hop routing in [14,16] focused on the issues of best shortest path algorithms, optimal search techniques for satisfaction of delay constraints, and distributed algorithms for on-line implementation.

The third and final problem area addressed in this part of the research program was that of network design. The particular design problem examined was one of optimal capacity assignment. In this problem, one wishes to specify the capacity for each channel in a network in order to minimize the average message delay subject to a constraint on the total

capacity available for assignment, or, equivalently in an economic sense, the amount of money available with which to purchase capacity. The problem and its dual, in which the total capacity is minimized subject to an average message delay constraint, have been treated extensively in previous research. In [12], a version of the dual problem was considered wherein the minimization of capacity is subject to a set of one or more end-to-end average message delay constraints. Owing to the latter, the research in [12] is related to that in [13] described above. The motivation for the work in [12] came from the fact that satisfaction of the usual average message delay constraint may not always provide acceptable delay for certain source-destination node pairs such as those involved in tactical voice and data communications. This research yielded procedures for the required capacity assignment. The underlying problem was shown to be that of solving a system of nonlinear algebraic equations for which a general nonlinear programming formulation was provided.

IV. PUBLICATIONS

Given below is a chronological listing of all publications which have resulted from the research conducted under this grant.

1. J. S. Meditch, "Inverses for discrete-time stochastic linear systems," Proc. 1978 Conf. on Info. Sci. and Systems, Baltimore, Md., Mar. 1978, pp. 124-128.
2. J. S. Meditch, "On the representation of optimal fixed-lag smoothers for continuous-time random processes," Proc. 16th Allerton Conf.

on Comm., Contr. and Comput., Univ. of Ill., Urbana, Ill.,
Oct. 1978, pp. 192-201.

3. J. S. Meditch, "On the representation of optimal fixed-lag smoothers for continuous-time random processes," Intl. J. Contr., vol. 30, no. 3, Mar. 1979, pp. 447-458.
4. O. M. Micheloud and J. S. Meditch, "Partial inverses for multi-variable linear systems," Proc. 1979 Conf. on Info. Sci. and Syst., Baltimore, Md., Mar. 1979, pp. 543-548.
5. J. S. Meditch, "Stable continuous-time fixed-lag smoothers for stationary random processes," IEEE Trans. Automat. Contr., vol. AC-24, no. 2, Apr. 1979, pp. 335-337.
6. J. S. Meditch and J. C. Mandojana, "A decentralized algorithm for optimal routing in data-communication networks," Proc. 18th IEEE Conf. on Decision and Contr., Ft. Lauderdale, Fla., Dec. 1979, pp. 134-140.
7. O. M. Micheloud and J. S. Meditch, "Observers for multivariable systems with inaccessible inputs," ibid., pp. 849-852.
8. J. S. Meditch, "An approximate solution of the optimal flow assignment problem," Proc. 1980 Conf. on Info. Sci. and Syst., Princeton, N. J., March 1980, pp. 51-52.
9. J. S. Meditch and J. C. Mandojana, "A decentralized algorithm for optimal routing in data-communication networks," Large Scale Systems, vol. 1, no. 3, Aug. 1980, pp. 149-157.
10. J. S. Meditch, "Large-scale system network problems," Proc. 1980 IEEE Intl. Conf. on Ckts. and Computers, Port Chester, N.Y., Oct. 1980, pp. 106-111. (Invited Paper).

11. J. S. Meditch, "Modeling and performance analysis of the packet formation process in packet-switched telecommunications," Proc. 18th Allerton Conf. on Comm., Control, and Computing, Univ. of Ill., Urbana, Ill., Oct. 1980, pp. 333-338.
12. J. S. Meditch, "Optimal capacity assignment in message-switched networks subject to end-to-end delay constraints," Proc. 19th IEEE Conf. on Decision and Control, Albuquerque, N.M., Dec. 1980, pp. 149-151.
13. J. S. Meditch and F. D. Gorecki, "Minimum hop flow assignment and routing in computer-communication networks," ibid., pp. 634-636. (Invited Paper).
14. F. D. Gorecki and J. S. Meditch, "A dynamic programming approach to minimum hop flow assignment in message switched telecommunication networks," Proc. 8th Triennial Congr. of the Intl. Fed. of Automat. Control, Kyoto, Japan, Aug. 1981, vol. 11, pp. 148-153.
15. J. S. Meditch, "Analysis of the packet formation process in packet-switched networks," Proc. 19th Allerton Conf. on Comm., Control, and Computing, Univ. of Ill., Urbana, Ill., Sept. 1981, pp. 413-420.
16. J. S. Meditch and F. D. Gorecki, "A distributed minimum hop routing algorithm," Proc. 20th IEEE Conf. on Decision and Control, San Diego, Calif., Dec. 1981, pp. 392-397.

V. PH.D. RESEARCH

Research leading to the following doctoral theses was supported in part by this grant. All work was done in the Department of Electrical Engineering, University of Washington, under the supervision of the Principal Investigator, Professor James S. Meditch.

1. O. M. Micheloud, "Inverses for Linear Multivariable Systems," Dept. of Elec. Engr., Univ. of Washington, Seattle, Wash., Apr. 1979.
(Also issued as Tech. Rept. No. 216, April 1979.)
2. J. C. Mandojana, "Routing Strategies for Store-and-Forward Data-Communication Networks," Dept. of Elec. Engr., Univ. of Washington, Seattle, Wash. Aug. 1979. (Also issued as Tech. Rept. No. 218).
3. F. D. Gorecki, "Modeling and Performance Optimization of Large-Scale Data-Communication Networks," Dept. of Elec. Engr., Univ. of Washington, Seattle, Wash., June 1981. (Also issued as Tech. Rept. No. 221.)

VI. PROJECT PERSONNEL

Professor James S. Meditch served as the Principal Investigator throughout the term of the grant. The following pre-doctoral research assistants were supported in part by the grant during their Ph.D. thesis research: O. M. Micheloud and J. C. Mandojana during 1978-79, and F. D. Gorecki during 1979-81. Their Ph.D. Theses were cited in Section V above.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) <p>Research conducted under AFOSR Grant 78-3546, Control Systems and Networks, during the four-year term of the grant, 1 February 1978 to 31 January 1982, is summarized and highlighted. The work is classified into the two major categories of (1) control systems and (2) networks. Within the former, new results are reported in the areas of vector-delay inverses, pseudoinverses, fixed-lag smoothing realizations, and the design of multivariable control systems using system inverses. In the second category, the focus is on the problems of modeling, analysis, optimization, and control of large-scale, distributed networks</p>		

for C³. Specific topics dealt with include hierarchical control, decomposition, and distributed intelligence in network performance optimization, the theory of aggregated imbedded Markov chain models and distributed control of large-scale computer-communication networks, the packet formation process in packet-switched networks, centralized and decentralized optimal flow assignment and routing in networks via the minimum hop technique subject to message delay constraints, and minimum cost channel capacity design of networks. Listings of the publications and Ph.D. theses resulting from this grant are given.